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Walking Quadrupedal Platform

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A Major Qualifying Project Report submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the Degree of Bachelor of Science in Robotics Engineering

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Key Words and Abbreviations

The following paper will abbreviate some commonly used words to avoid repetition. The abbreviations used are standard in industry and are outlined below.

Major Qualifying Project (MQP)

Worcester Polytechnic Institute (WPI)

Controller Area Network (CAN)

Proportional Integral Derivative (PID)

Series Elastic Actuation (SEA)

Degree of Freedom (DoF)

Pulse Width Modulation (PWM)

Center of Gravity (CG)

Lithium Polymer (LiPo)

Inertial Measurement Unit (IMU)

Thermoplastic Polyolefin (TPO)

Revolutions Per Minute (RPM)

Computer Aided Design (CAD)

Field Programmable Gate Arrays (FPGAs)

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Abstract

The following paper details the work done to complete a walking quadrupedal major qualifying project. The goal of this project was to continue developing a functioning quadrupedal platform for the WPI robotics department. The quadruped is a forty-pound robot with four independently moving legs built by a previous MQP. This project consists of testing and implementing motion control systems. The primary goal of the project was to ensure that the robot quadrupedal chassis built by a previous MQP could move stably and intelligently so that it can be useful for future projects. Three main motion gaits were studied, a crawl gait, a walking gait, and a turning gait. The project implemented stable motion for the three gaits mentioned. In addition, the team also made significant system design improvements in the structure, electrical circuit, and code.

1 Introduction

Quadrupeds by definition are any animal that moves using four legs, such as dogs. Having four legs gives them more balance when moving. These quadrupeds are the core reference point for this project. Animals such as dogs use their four legs to stably crawl, walk, run, turn and jump. Because of this they are often referenced in the design of robots whose goals are to maneuver stably through varying terrain, using the four legs for extra stability. Currently, the WPI robotics engineering department does not have a simple quadrupedal platform that can easily withstand modifications. A platform of this nature could be used to test many different systems, sensors, and more.

The following project aims to develop this system for future use. The project builds off the "Quadruped Robotics Platform" (Armsby, et al.) MQP completed in May 2018. This project designed the mechanical quadruped chassis and preliminary communication code structure. Using this base, this project focuses on stable motion.

The project is completed over the course of four terms on the WPI scholarly year calendar, each term being about seven weeks in length. The project was completed during WPI's 2018-2019 academic year. The primary focus of the project was to research, analyze and test the controls needed for stable motion on the quadruped system. This included research on motion gates and physical tools to accomplish those gates. The team also had to create a robust communication base between all the micro-controllers and sensors to make sure the motions could be controlled in real time.

Working off a previously built quadruped came with many constraints and issues to consider. The first significant issue encountered was a lack of documentation. The robotic chassis was designed under the same time constraints of this one so finding time to properly log every decision was most likely difficult to do while designing the system. While the robot chassis was designed for motion, the former MQP team's scope did not include fully testing the system. As a result, many decisions to either modify or replace portions of the quadruped base had to be made. Every decision was carefully analyzed as the project had both time and budget constraints.

By the completion of the project, the team developed a system for stable motion for the crawl, walking, and turning gaits. While the gaits may not be completely finished, it shows a proof of concept for the quadrupedal robotic platform.

2 Background

There was a lot of work to be done at the beginning of the project to set the scope. The team had to analyze the status of the robot prior to starting any modification and research on quadruped motion gaits. The following section details all the background information the team gathered at the beginning of the project.

2.1 Robot Status

Since this project builds off a previous MQP, an analysis of the robot's status is necessary. Since the previous team was under a tight time constraint, there was little documentation. This resulted in a steep learning curve of the system.

The robot designed weighed about forty pounds. The chassis is made entirely of custom cut metal. It included four independently moving legs with two degrees of freedom each. The system consits of three types of controllers, a MicroZed 7010, Teensy 3.6's, and Talons. Each joint was powered by Vex Pro 775 Motors through Vex Versaplanetary Gearboxes. The entire system was powered by two larger twelve-volt lawn mower batteries, weighing about 5 pounds each.

The system architecture the previous MQP team implemented used three micro-controllers, as mentioned. The main controller is the MicroZed, containing all the main code. Each of the four legs had their own Teensy 3.6 running the proportional-integral-derivative (PID) controllers, totaling to four Teensys. Each joint had its own designated talon serving as a motor controller, making eight talons total on the chassis. They had one-way communication from the MicroZed to the four Teensy 3.6's. Each Teensy is also responsible for a single liquid crystal display (LCD) screen that displays joint positions, and other information important for debugging. The Teensys then had two-way communication to the Talons, which handled a second level of PID for each joint. All communication was done through various can-buses. This system posed a few issues. The team needed fast two way communication to get the information from various sensors in real time for motion controllers run from the MicroZed. The team also saw that running two different PID loops made perfectly tuning the leg motions very difficult. The Teensys also had one-way communication from custom foot sensors the previous team designed, however, this was not fully implemented or tested.

As mentioned, the robot ran off two twelve-volt batteries. These batteries powered not only the micro controllers and motors but also the sensors. Each joint had a 180 degree potentiometer, making it eight total. These batteries also powered the custom foot sensors. These sensors are casted to fit the feet of the quadruped. They consist of a 3x3 array of LPS25HB absolute pressure sensors as shown in Figure 2.1. These sensors were tested independently before they were attached to the robot. The previous team did very basic testing of these sensors and found a potentially linear correlation between load and the sensor readings. These sensors were attached to the quadrupeds feet but never wired in or fully implemented. The preliminary tests that the previous team conducted is not enough to currently interpret each sensor's reading.

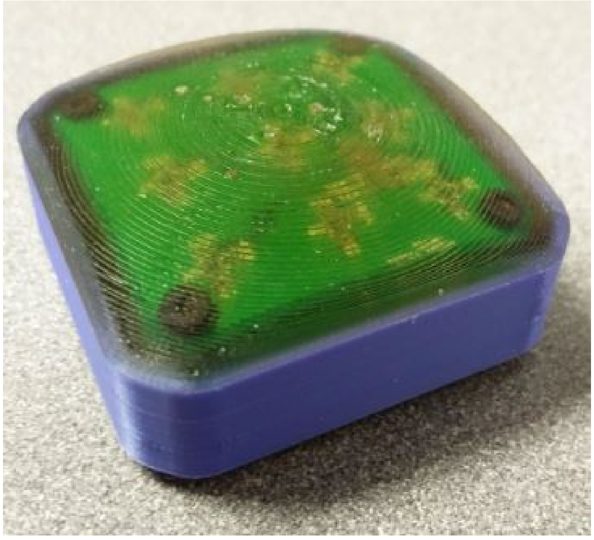


Figure 2.1: Custom Foot Sensor (Armsby, et al.)

As mentioned each joint was independently actuated by a single motor. However this was not direct driven; it goes through both the gearbox and a series elastic actuation system. The series elastic actuation system while installed was not being utilized to its full potential. Each leg had potentiometers to read the series elastic actuators. The sensors were not wired or tested. This system for driving the motors also created a lot of slack. This system will be further discussed in the next section.

Given this status, the team identified potential issues that need to be addressed. The series elastic actuators caused a lot of control issues because of the slack. Since the foot sensor was also not thoroughly tested and implemented this poses another issue that needs addressing. In the process of addressing the foot sensors the foot also needs to be redesigned. Since the robot is also expected to run in real-time, it is also essential to account for reaction and cycle time. All of these design decisions will be addressed in the sections to follow.

2.2 Foot Design

As mentioned the custom foot sensor that the team initially designed was not thoroughly tested. Implementation of the foot sensor had also not yet begun on the quadruped. So other designs were considered to see what the best course of action was. The team needs to make sure that the robot can move and stand stably. For reference on foot design, the team also looked towards quadruped animals. Specifically, prosthetics as the one shown in Figure 2.2 as they need to durable and allow stable motion for all of an animal's gaits.

Figure 2.2: Dog Leg Prosthetic (Prosthetics for Dogs and Other Pets

2.3 Gaits

Understanding motion gaits is vital for stable motion. ”A gait is defined as the periodic pattern of locomotion characterized to a specific range of speed” (Meek, Sanford). These gaits have been optimized for efficiency through years of evolution, so they are often used as a reference for robotic motions. The team has decided to focus on three different gaits common in quadrupeds, a crawling gait, a walking gait, and a turn gait. There are several different animal gaits to use as a reference. One study analyzed and implemented a horse gait (Yu, Lianqing). The most common animal to reference is a dog’s motion gait. The gait is analyzed by tracking each joint’s motion shown in Figure 2.3. For this project, the team will reference gaits that were based on dog motions as their body ratio most closely resembles the robot’s. However since the former team only implemented two degrees of freedom per leg preliminary gaits had to be modified for two joint motions.

2.3.1 Crawl Gait

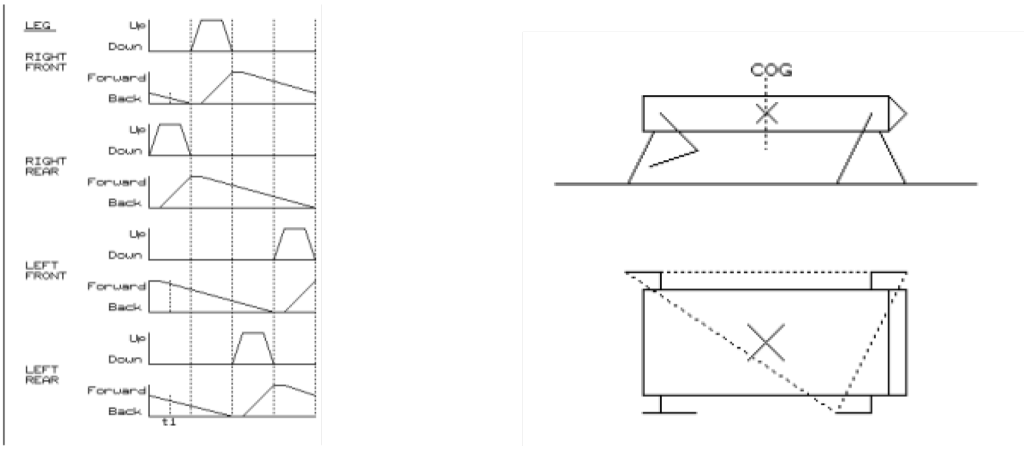
The crawl gait is the slowest quadruped gait. It is also the most stable since at any given time in the motion there are at least three feet placed firmly on the ground. In the crawl gait a foreleg starts the motion by lifting and moving forward; once it is planted on the ground the hind leg on the opposite side lifts and starts to swing forward (Hwang, Heeseon). This repeats until all four legs have shifted forward, ending a single gait step. While some gaits are dynamically stable while

Figure 2.3: Quadruped Gait Analysis(Liu, Wan)

in motion crawl gaits are constantly statically stable (Hwang, Youngil). Since there are constantly three legs on the ground the support area is triangular so the center of gravity of the robot can easily stay within the area through each motion. This can be seen in Figure 2.4. Many quadrupedal animals use their head or tail to shift their weight to ensure this. In robots common practice is to tilt the chassis, mimicking how some quadruped shoulders and hips dip during motion to keep the center of gravity inside the stable area.

2.3.2 Walk Gait

A quadruped's walking gait is typically faster than the crawl gait, however, it is a lot less stable. Unlike the crawl gait which is constantly statically stable the walking gate is dynamically stable. This means that the robot will be stable



(a) Quadrupedal Crawl Gait (Liang) (b) Quadrupedal Center of Gravity (Liang)

Figure 2.4: Concepts of quadrupedal Crawl Gait

while in motion but it is not stable at any single moment in time. This is because the walking gate only has two legs on the ground at any given time. This shrinks the area of stability, in which the center of gravity needs to lie. The only stable position for the center of gravity to be is along a straight line connecting the two legs on the ground. Like the crawl gait, the walking gait can be broken up into four programmable parts. The robot lifts two diagonally opposite legs forward and once they are above the correct position they are planted back on the ground. Because it moves two legs at once each step can be longer. Many quadruped animals stay stable by catching themselves and using the impact to push forward to the next part of the walking gait. However, some quadrupedal robots instead shift their center of gravity by tilting their body while the legs are being raised. The second method, while being generally slower, is more stable and helps control the impact.

2.3.3 Turn Gait

While crawling and walking gaits allow the robot to move laterally a turning gate needs to be explored to make the robot useful for future projects. Turning gates are a little more complicated than walking and crawling. There are two methods of turning, using two degrees of freedom per leg and sliding the legs that don't step, or using three degree's of freedom to pivot the legs. Most robotic quadrupeds utilize three degrees of freedom per leg. One example of a robot designed to both move laterally and turn is shown below in Figure 2.5 (Yu, Lianqing). This is a common configuration for quadrupedal robots, a shoulder joint at the top of each leg with the axis of rotation along the length of the robot and two joints below with the axis of rotation along the width of the robot.

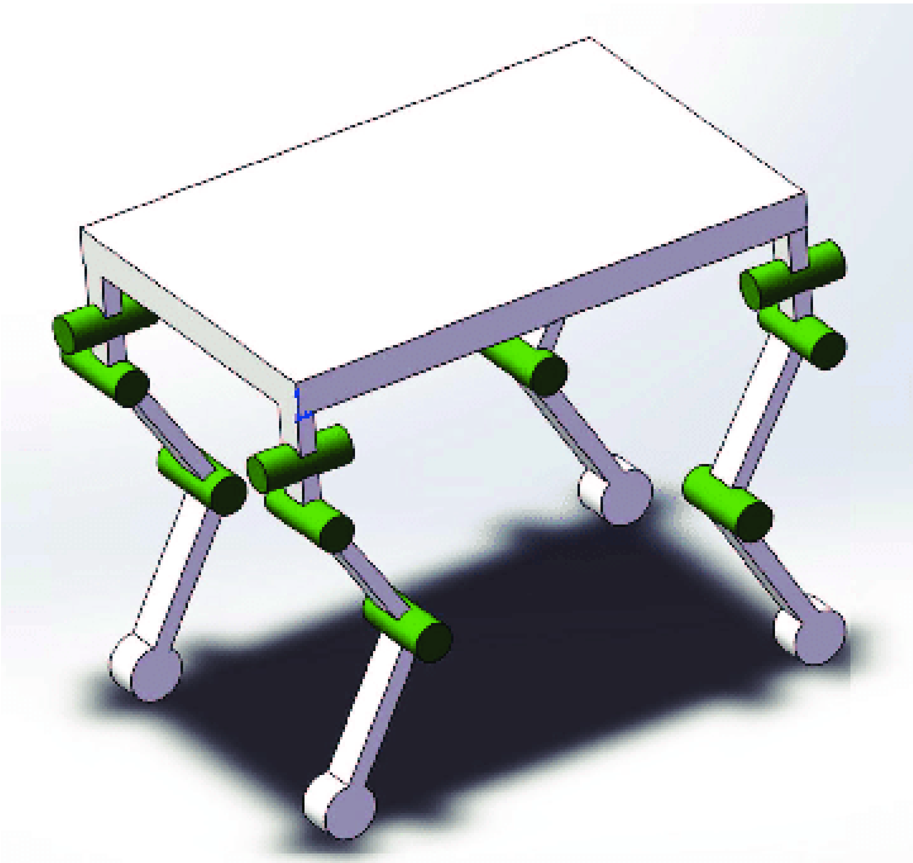


Figure 2.5: Turning Quadruped (Yu,Lianqing)

2.4 Series Elastic Actuation

Series Elastic Actuation (SEA) is a means to deal with impact (Hurst, et al.). It is often used in robotic arm/leg applications to decouple the motor gearbox from the joint. The main use of Series Elastic Actuation is torque control (Hunter). It has the potential to sense the impact torque of the system when correctly implemented. A basic diagram of a series elastic actuation system is shown in Figure 2.6. The former team intended to use potentiometers on the system to measure the torque. This means that the system could potentially detect when the robotic limb makes impact and how much pressure is being applied. A detailed digram of the former team's SEA is in the appendix. This could be very useful in feed forward control. However, there are many issues with SEA. The main issue in this system is slack, as previously mentioned. Series elastic actuators can also cause "relatively high-frequency oscillation that the software controller cannot damp"(Hunter). The system also limits acceleration, causing the system to slightly jiggle upon contact. The team considered these factors in the final design. Considering the application of the series elastic actuation and what is important to achieve the desired result is very important. For example, Rethink's

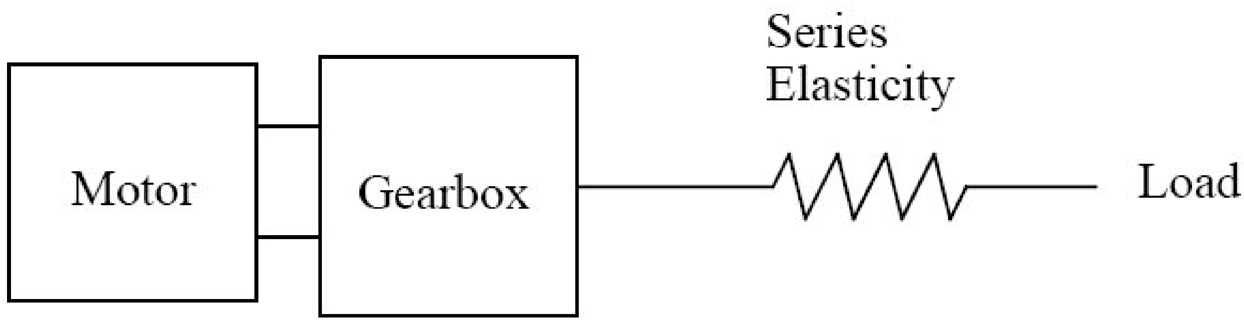


Figure 2.6: Series Elastic Actuation Model (Rohrer, Fabien)

robot, Baxter, using SEA in its arms. A vital factor of Baxter's application is to work with people collaboratively. The SEA allows the robot to sense force. ”Force sensing gives Baxter a light touch that not only protects people working nearby, but also enables the robot to know when to stop” (Fitzgerald) When implemented correctly series elastic actuators have been shown to ”guarantee higher stability robustness in force control” (Calanca). An example where SEA could be of benefit is the ABB industrial arms. These arms have force sensing and can stop when they detect collision (Integrated Force Control). However, the arm is very rigid and takes more force to actively stop. In this case the slack introduced by a SEA system could make the collision stopping safer. The slack would automatically move when it collides with little additional power, and with real-time reaction speed. There are many benefits and downsides to using a series elastic actuation system and the application must be thought out.

2.5 Control Dynamics

Regardless of the gait, each phase will have different system requirements. A good control system is vital for stability of the robot. There are a few ways of approaching this. The most common is through some feed-forward system. ”The main purpose of using feedback is to compensate for external disturbances and for model uncertainties” (Visioli, Zhong). In this project the external disturbances and discrepancies are caused by the system's reactions at different points of the motion phase. Physical impacts that cause disturbances are system slack or slightly different angles of impact. Feed-forward control can predict system requirements, taking into account these disturbances. The system can also run a proportional integral derivative (PID) controller. This is a system in which systems respond real-time to differences in the sensor's actual readings and the expected readings to get it as close to the ideal configuration as possible. The team considers both control systems for the robot.

Any kind of control system allows robots to react to their environment based on a variety of sensors. For example, an inertial measurement unit (IMU) could be used to detect if the robot starts to tilt too far in any one direction. Another method is to use a sensor to detect which feet are on the ground to ensure the right contact is being made. Another is to get feedback on joint positions to insure that they are in the expected spot or if the motor is having to exert extra torque to keep the joint in position. These methods could also be used together to create a better model of the robot's status while in motion. The sensors can also be analyzed differently to affect how the robot reacts. Impact sensors, IMU's and torque feedback can be used to determine an estimate of where the robot's center of gravity is. If the center of gravity is calculated to have moved out of the stable area the robot can compensate by shifting its weight. The weight on each leg could also be calculated by these sensors so instead of focusing on shifting the whole robot's weight the goal would be to apply sufficient torque to sustain individual leg's position.

3 Project Expectations and Timeline

This project was completed over the course of the 2018-2019 school year. The team completed 1/3rd of a credit in A, B, and C term, completing the requirement of a full credit of MQP. However, the team extended the project by a 1/6th credit in D-term to focus on finalizing the documentation.

The expectation for this project was to prove the robot's capability of stably automated motion. The project is successful if the robot can move stable and make use of the chosen control system. The project needs to show strong potential as a useful moving platform.

As mentioned, the goal of this project was to build off a previously built MQP. As a result, a detailed time-line of work was only created after a comprehensive assessment of the robot status was completed. This timeline changed throughout the term based on the current progress. For example, the team had not originally planned to implement a third degree of freedom but since the crawl and walk gait were implemented as quickly as they were the team decided to add this task.

This section details the finalized timeline.

The project started in A-term of WPI's academic year, spanning from August 2018 to October 2018. Since this was most of the teams first interaction with the robot there was a sharp learning curve. During this term preliminary movement tests were conducted on the robot to gauge the robot status. To do this the team ran inverse kinematics code for both joints on each leg. The team also looked into the communication protocol between the MicroZed and Teensys. During this phase essential decisions on the scope and direction of the project were made. The team identified parts of the project that needed to be redesigned. This process revealed a number of areas that need improvements. Mechanical design, power transmission, and communication, were all identified as areas of improvement. These issues were addressed throughout B term.

During B term the expectation was to address the issues identified in B-term and start implementation of the crawl gait. To do so the team had to custom design and manufacture parts for the robot. The term was also spent re-designing the communication between micro controllers for time efficiency. The crawl gait was implemented sooner into B-term than expected so the team also started the walking gate. Since this was initially planned for C term the team adjusted the timeline for C-term.

C-term, being the last full project term it was the most malleable. At the start of A term it was decided to work on the walking gate in this last term. However we moved our time line up to include the implementation of the third degree of freedom and turn gait and the finalization of the walking gait.

The last term of work was D-term. Unlike the prior terms it only consists of a 1/6th credit. The team decided to extend the MQP to focus on documentation. This includes preparation for poster presentation day, the final paper, and the eCDR.

Table 3.1 below shows a detailed breakdown of the goals for each term.

A-Term	B-Term	C-Term	D-Term
Evaluate Robot Repair Gait Design Kinematics	Re-design Foot Gait Tests Install Sensors Crawl Gait	3rd DoF Batteries Turning Gait Walking Gait	Final Poster Prep. Final Paper

Table 3.1: Term Goals

4 Metrics of Success

As stated in the introduction the main goal of the project is to ensure that the quadrupedal robot has the potential to be a useful tool for the WPI robotics department. The team has defined potential usefulness by the quadruped's ability to move stably. This includes creating a stable walking, turn, and crawl gait using onboard tools. The walking gate should move faster than the crawl gate in order to be considered a successful implementation. The turn gate should be able to stably turn at least 45 degrees. To accomplish this the team needs to successfully analyze decisions regarding modifications and additions to the existing system. It will also require successful implementation of a controls system that responds in real time to the robot's status. The successful completion of the individual tasks outlined in the project time-line are also taken into consideration for the overall project success. The team also has to prove that the modifications to the quadruped have made it a better system than the one the team started with. This will prove that the team's work has made progress in the development of a useful tool. When measuring success, it is also important to account for the team's ability to react to decisions efficiently and effectively, as well as the completion of tasks in a timely manner.

5 Design Platform

The following design platform section details the work done to complete the project and the methods used to approach tasks and issues.

5.1 Code Structure

An essential part of this project is the code, and its structure. Most of the work done by all members involved included writing code for either motion or communication. The following explains how the team approached the system and it's requirements from a coding and system architecture perspective. There were two main types of controllers that needed to be programmed as mentioned in the "Robot Status" section above. The team refers to the MicroZed as the main controller, and the Teensy's as the leg controllers.

5.1.1 Central Controller

The central controller of the quadruped is a MicroZed 7010 FPGA. This controller computes all of the kinematics for every leg of the quadruped as well as plan leg trajectories to send to the individual leg controllers. The state machines to run the quadruped gaits are handled here. The MicroZed is utilizing its two Controller Area Network (CAN) lines to allow for a unique CAN line to control an entire side of the Quadruped. The central controller can request at any time a multitude of information recorded by each leg controller such as current position, foot contact switch reading, and motor torques or voltages.

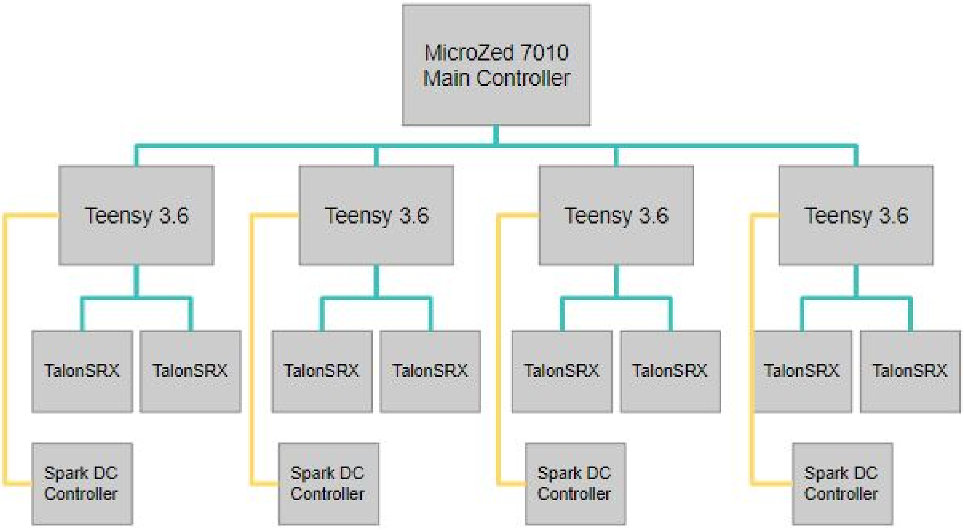
The central controller handles a lengthy initialization routine to set up the quadruped to function as desired. This initialization routine involves sending calibration values to each leg controller. The calibration values had been determined through our own testing. These calibration values only needed adjustment if a potentiometer had to be adjusted or fixed. Part of this calibration is inverting the direction for certain motor controllers as well as reading values from the potentiometer in the opposite direction. Lastly PID values are distributed from the central controller to the leg controllers to make adjusting PID values a quick process. The initialization routine also initializes all of the CAN bus lines and informs the leg controllers to activate their motor controllers.

All of the kinematics done in the central controller is handled by a class called movementPath.cpp. It includes inverse kinematics functions for two DoF, three DoF, and even variants to handle whether we want the leg's elbow in or elbow out. Even the circle inverse kinematics required for turning is handled by the movementPath class.

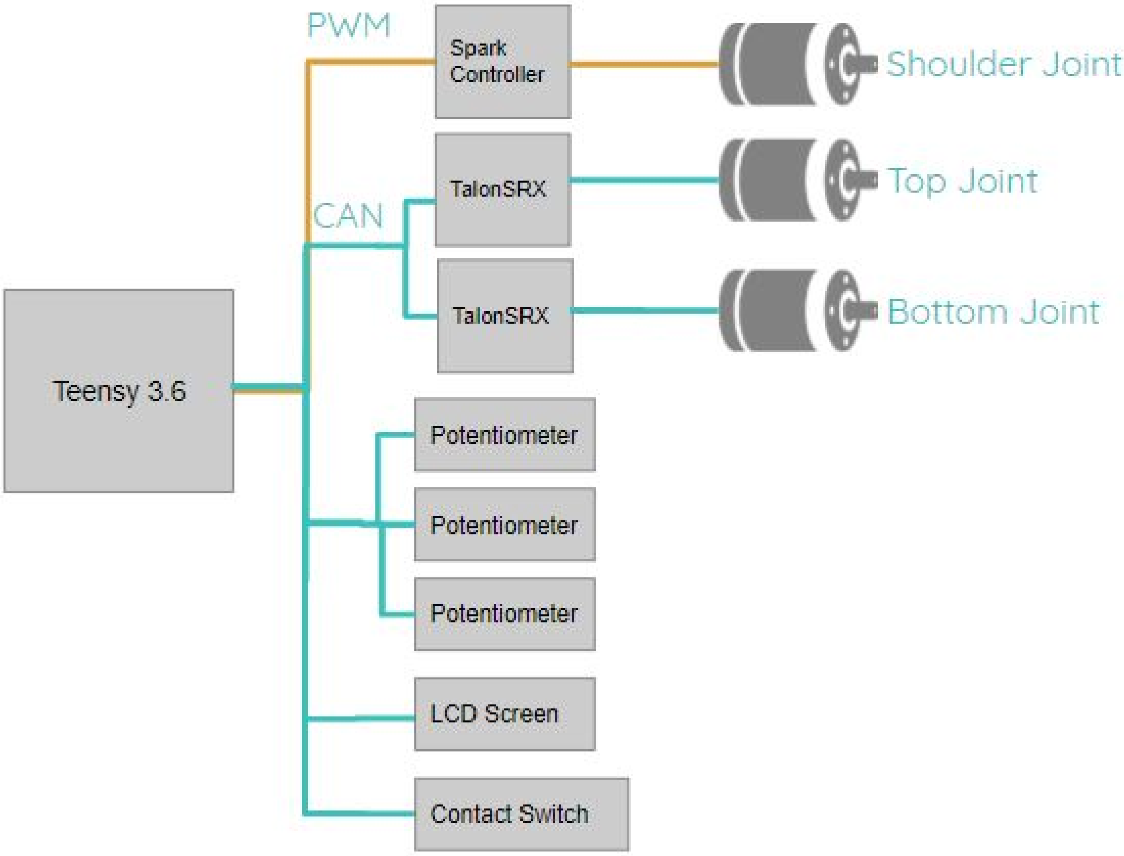
All of the state machines handling the crawl, walk, and turn gait are conducted by the central controller. The state machines generate trajectories and iteratively pass joint space values to each leg individually via the CAN bus. All of the state machines are parameterized so that the speed of the gait, step length, step frequency, and step location can be adjusted or changed.

5.1.2 Leg Controller

The quadruped contains four leg controllers each of which are a Teensy 3.6. The leg controllers receive directions from the central controller via a CAN bus. Each controller needs to have independent control over three motors, so each Teensy is also connected to three motor controllers. Two of those motor controller are Talon SRX's which are communicated with over the Teensy's second CAN line. The third motor controller is a REV Spark motor controller which is controlled via PWM. Diagrams showing these relationships are shown in Figure 5.1. Each motor controller is only doing voltage control for their own motor. The PID feedback loops control the set voltage assigned to each motor controller. The legs PID loops operate completely independent from the central controller. The central controller only gives each leg controller desired joint positions, but calculating the output of the PID in real time is inside each leg controller. Each leg controller can also be given a feed-forward value that is proportional to the amount of weight on the leg. Calculating the subsequent additional voltage for each joint due to the feed-forward value is also handled inside the leg controller.



(a) System Structure



(b) Single Leg Structure

Figure 5.1: System Structure

In a sense, the leg controller only acts as a low-level controller that does what the central controller wants it to do. All of the low-level looping and logic can then be ignored by the central controller.

5.1.3 Feed-forward Controller

A feed-forward controller was implemented to aid the control system from relying solely on a PID controller with imperfect gains. The feed forward controller aims to counteract expected forces on the joints from the weight put on each leg. A diagram of the controller is seen in Figure 5.2. New functionality on the Leg Controllers was added to provide an estimated weight on the leg controller's own leg. The leg controller takes this estimated weight and calculates torque, based on a static model, needed to maintain that weight given the current joint angles. The calculated torque is multiplied by a tuned gain to then add resulting voltage to the control of that joint. The central controller calculates the weight to send to each leg based on a model keeping track of the Center of Mass relative to each foot and which feet are contacting the ground.

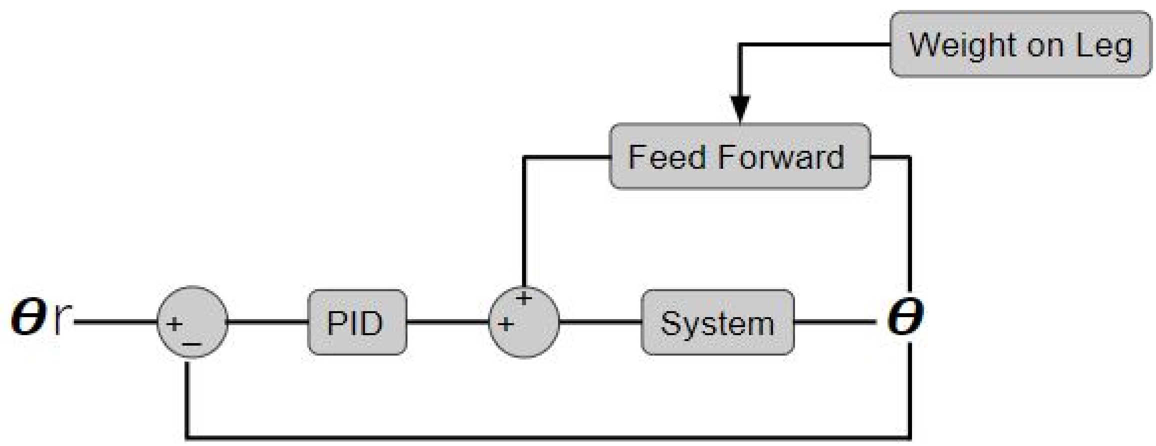


Figure 5.2: Control Block Diagram

Since the legs joint are expected to be in stall during loads that require feed forward control there is linear relationship between output torque and voltage. This is used to create feed forward equation that increases voltage on the motor. A constant gain was used to tune the feed forward controller. The feed forward gain is denoted by K_f. The Teensy is given estimated weight from the central controller denoted by W in the equation. l_1 and l_2 are link lengths and q_1 and q_2 are joint angles. The feed forward controller calculates torque on each joint with W, l, and q. K_f was then calculated and tuned based on motor specs to counteract the torque on each joint. The feed forward equations are expressed in equations 5.1 and 5.2.

$$\tau_1 = K_f * (W * (l_1 * sin(q_1))) \tag{5.1}$$

$$\tau_2 = K_f * (W * (l_2 * sin(q_1 + q_2))) \tag{5.2}$$

5.2 Electrical Design

As explained in the leg controller section the Teensy's each had their own set of actuators and sensors for an individual leg. In order to produce an intelligent motion, gait feedback is required to understand the robot's status in the environment. This is why we needed to ensure that we had useful sensors. The first sensor the team used for control was the potentiometer on each joint. The previous team had placed cheap plastic 180 degree potentiometers that very easily broke if they were not perfectly aligned. The team replaced these with more durable 270 degree potentiometers. At first 100k ohm potentiometer were used, but it was discovered that the resistance was too high and the potentiometer readings were noisy. Replacing the potentiometers with 10K ohm ones fixed the noise problem. These were important has the PID controller was used to control the legs position so the angle of each joint was essential information. The three potentiometers you see in Figure 5.3 are for the three joints and are read via simple analog in wires. The same goes for the button at the bottom of the foot. This button allows the main controller to know if an individual foot has made contact with the ground. There is one on each foot and it is connected to a digital port on the Teensy. The motor controller for the shoulder joint motor is also connected to the Teensy via PWM. The other two motor controller joints are connected through the Teensy via CAN bus. The reason the shoulder motor controller is different is because it was a modification added later on in the project. The team did not have enough funds to purchase the same type of controllers that the previous team had installed. They had installed TalonSRX's that only communicated through CAN bus, while the current team purchased and installed spark motor controllers that only communicated through PWM.

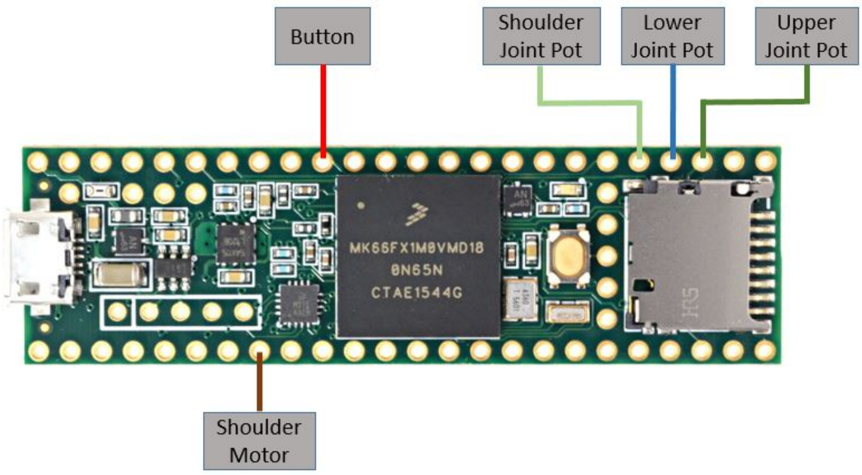


Figure 5.3: Teensy Input/Output Wiring

5.2.1 Power Supply

Since a primary function of the quadruped is mobility, being limited by a bulky power source is not ideal. The previous MQP had used two lawn mower batteries, with a combined weight of thirty-pounds. This could not be supported on the robot so the batteries had to be placed on a nearby surface, tethering it. These batteries were capable of running the robot in continuous motion for about six hours. The team replaced these batteries with much lighter, higher density LiPo batteries. These batteries weighed about two pounds each. However, these LiPo batteries only have about a third of the capacity of the lawn mower batteries. Since these are significantly lighter they can be mounted on the robot's chassis, so the robot is un-tethered. The batteries are mounted such that they affect the center of gravity of the robot evenly from the center of the quadruped. The team decided this added mobility was worth the significantly lower run time. Figure 5.4 shows a size comparison of the old and new batteries.

Figure 5.4: Old(back) and New(front) Batteries

5.3 Gait Design

Each gait was chosen for the specific capability's it shows. The crawl gait displays static stability, the walk shows speed, and the turning displays the use of a third DoF. Each gait needed to be analyzed and broken down into something programmable.

5.3.1 Crawl Gait

The crawl gait involves the simultaneous movement of all legs, but only one leg at a time should ever leave the ground. Due to always having at least three legs in contact with the ground, the crawl gait inherently should be a more stable gait for the quadruped due to the gait always allowing for static balance. The quadruped can shift its CG to a desired location where upon lifting its leg the CG will still remain inside the support polygon of the remaining three legs. The Quadruped can continue shifting its CG in between steps to maintain static balance when lifting each leg. The specific crawl gait utilized by the team takes advantage of the parallelogram where upon lifting and placing one leg, the second leg on the same side can be lifted and moved without having to adjust the quadruped's CG to remain inside the support polygon. The gait should be able to take large steps while maintaining stability. A high speed of translation along with translating while stepping could allow the crawl gait to still move at a moderate pace despite only lifting one leg at a time. In Figure 5.5 the center of gravity is marked in red, and each dot represents a leg, blue signifying that the leg is lifted off the ground.

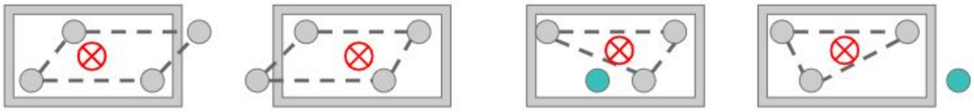


Figure 5.5: Crawl Gait

As visible in Figure 5.6 the entire crawl gait can be broken down into four programmable motions. Each motion lifts one leg. However, the robot still needs to shift it's CG to make sure the robot is stable. Doing this could allow for longer strides in each walking cycle since the center of gravity will be within the stable area longer if properly positioned during steps.

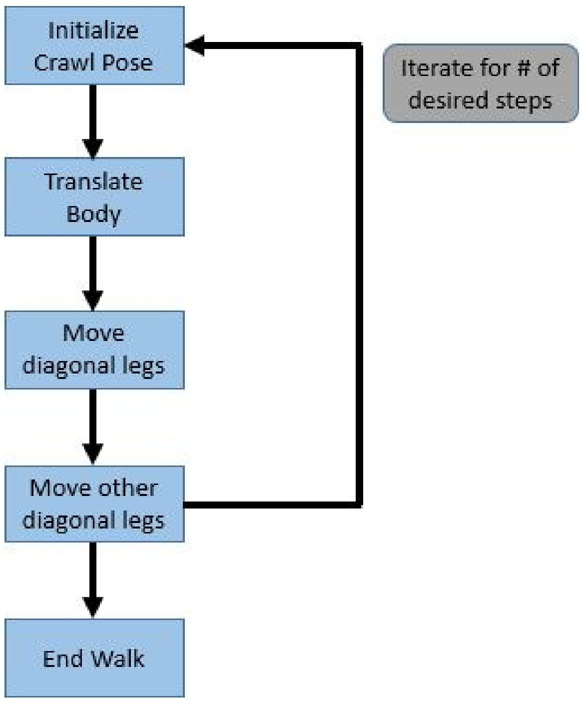


Figure 5.6: Crawling State Machine

5.3.2 Walk Gait

The walk gait is intended to be faster than the crawl gait by having two legs take a simultaneous step. Leaving only two legs on the ground is inherently unstable. However by positioning the CG as close to the line between the two feet remaining on the ground a step can be taken quickly enough to not lose balance. An inertial measurement unit (IMU) can improve this process of balancing along the balance line. However, the current quadruped does not have IMU implementation so a walk gait was developed to take quick steps with CG as close to the balance line as possible.

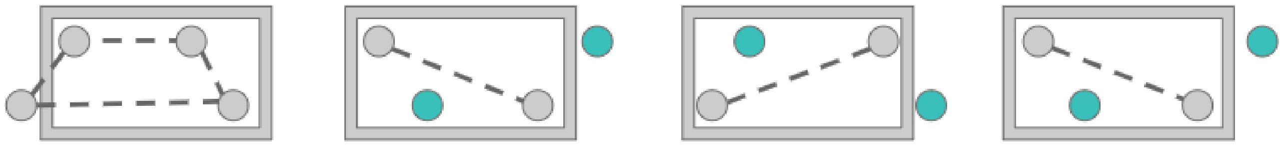


Figure 5.7: Walk Gait Diagram

The walk gait was first implemented by standing in place and lifting two legs up and placing them back down. Testing showed that beyond 150 milliseconds of time lifting the legs could cause the quadruped to tilt to far off center to an unrecoverable or unstable state. With 150ms in mind, the actual sequencing for the walk gait could be developed with a known maximum step duration. The stance for the walk gait utilized is a trapezoid, and the robot translates its COG to where the two front diagonals aligned with the COG. The other two diagonal legs could then take a simultaneous step forward and create a new trapezoid allowing the gait to repeat for the other two legs.

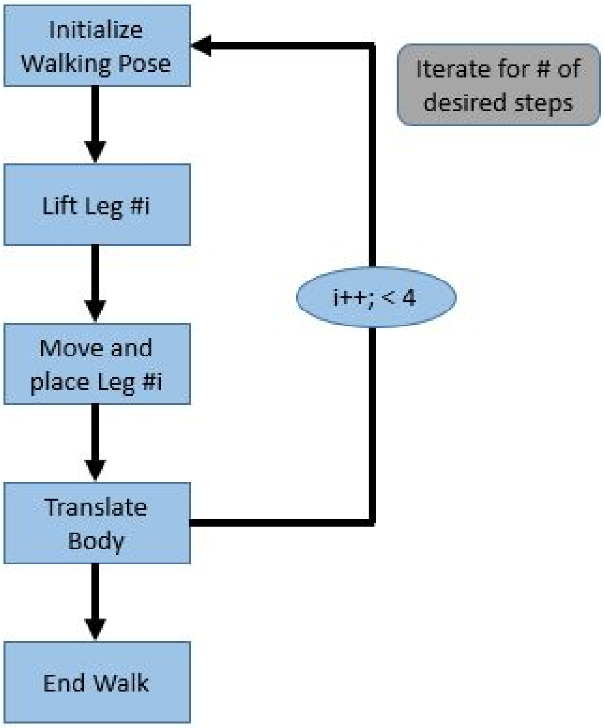


Figure 5.8: Walking State Machine

Turn Gait

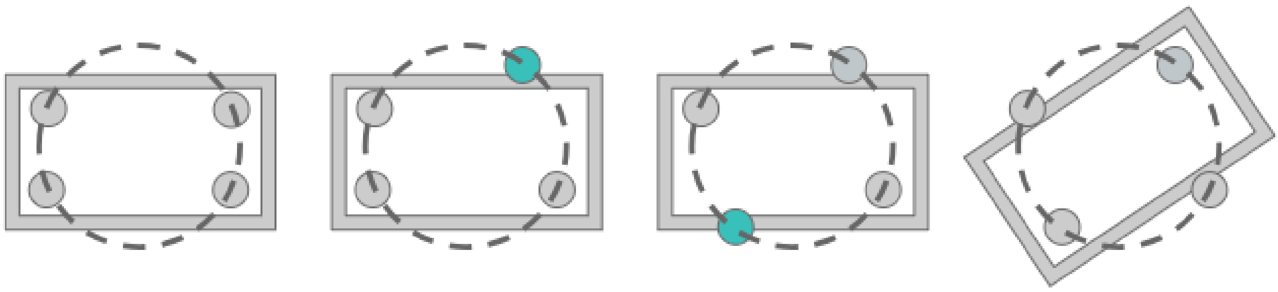


Figure 5.9: Turn Gait Diagram

The turn gait requires a third DoF to allow the legs to move into space perpendicular to their regular plane. The turn gait can be completed many ways kinematically. The method utilized for this quadruped relies and turning about a center circle of the robot. The turn gait only lifts one leg at a time so it is dynamically similar to the crawl gait. However these individual steps go into the y-axis to a point along a circle from the center of the robot. Two diagonal legs take these steps. Then the quadruped can simultaneously move every leg along the circle to cause the quadruped to turn. This gait was developed to allow an input parameter be how many degrees the turn would be. For the quadruped it was determined that kinematically a 60 degree turn should be possible, but would likely be much more unstable than smaller degree turns.

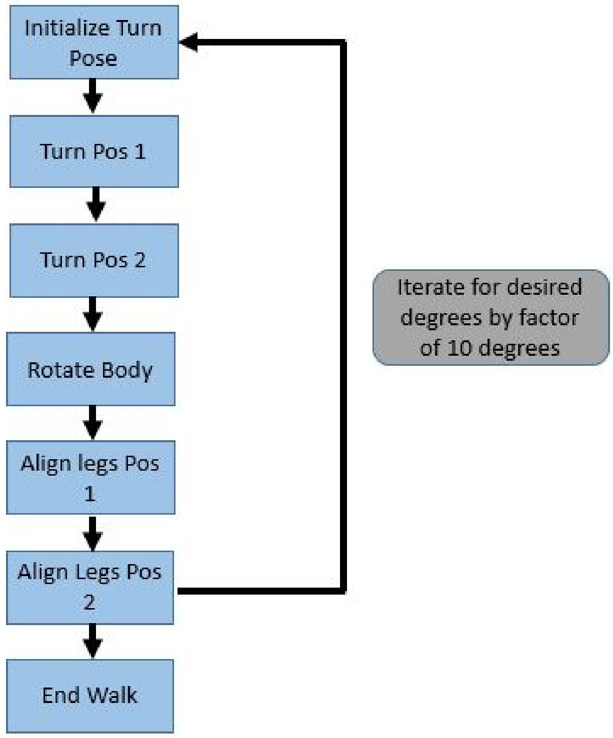


Figure 5.10: Turning State Machine

5.4 Mechanical Design

5.4.1 Foot Design

Early in the project the team decided to remove the custom foot sensors. This was a major decision for the project as it required designing a foot to replace it. Replacing it was important as having some type of feedback on the foots impact is useful information on the foot's position. There were several reasons for removing the custom sensors. The first is that while preliminary tests showed potential for pressure mapping not enough tests were conducted to show any direct correlation between the sensors readings and useful information. The sensors were also not fully implemented into the code for use nor was there sufficient documentation to easily figure out how to properly get and store the readings. While using the custom sensors was possible the team decided that it would be too time-consuming and did not fit within the scope of the project. Since the team already had to redesign the foot to replace the sensor it was also decided to tackle another issue with the previous foot design.

The previous MQP had implemented and used a rigid foot design. This makes stability difficult. A study by the University of Utah tested angle stiffness in roll, pitch, and yaw (Yazdi Samadi, Mohammad Reza). The study found that for a 6kg robot in a trot gait having over 100 N/m of stiffness was ideal for stability. However, having a rigid joint was also unstable because elasticity absorbs some of the impact. So this needs to be kept in mind while choosing a foot design. Through physical testing of the robot the team also found that a stiff ankle meant that the foot would make less contact with the ground depending on the angle of impact. This would cause instability with the trot as the robot was not able to use all the surface contact initially intended. With this in mind the team decided to re-design the foot.

Without the custom foot sensor and a need for an adaptable ankle, the team considered four types of designs. These designs had be plausible within the constraints of the project so they were assessed by the following categories: durability, cost, ease of manufacture, adaptability, compatibility, and utility. Durability is important as it has to take the weight of the robot, at least 15 pounds without breaking, the cost and how easy the foot is to manufacture is important because the team is restricted by funding and time. Adaptability, compatibility, and utility all correspond to how the foot will interact with the overall system. These metrics were used to analyze three types of foot designs:

Adaptive Foot:

This foot is designed to be flexible as it is elastic and conforms to the ground. Three mechanical toe joints also help the foot conform to the surface. This design would help with small bumps or variations in angle of the surface. It could potentially be entirely 3D printed from an elastic material. To satisfy the need for feedback the team would be able to attach a small limit switch on the bottom of the foot. The foot design can be seen in Figure 5.11.

Figure 5.11: Adaptive Foot (Eckert, Peter)

Rounded Foot:

A rounded foot design is exactly what it says in the name, simply a rounded bottom. This is one of the simplest foot designs. However, in order to make it compatible with the system and requirements it will have get a little more complicated. It will have to be made of elastic hollow material so that it can fit a sensor, either a limit switch or flex sensor. An example of this rounded foot design is visible in Figure 5.12.

Figure 5.12: Rounded Foot (S. Ivaldi et al)

Ankle Joint:

Much like the adaptive foot this design uses mechanical joints to conform to the surface. However, instead of the joints being on the toes there is one at the foot. The material would not need to be extremely flexible as most of the flex is in the ankle joint. The entire foot could be 3D printed and a limit switch attached on the bottom. The design the team used as a reference for this type of foot is shown in Figure 5.13.

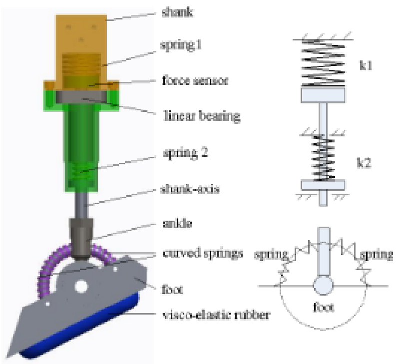


Figure 5.13: Ankle Joint (Lv, M.)

To analyze each option using these categories the team constructed a design matrix, as seen in Table 5.1. Each attribute was measured on a scale of one to three, with one being the worst, and three the best. So a higher total score indicates a better over-all ranking.

	Durable	Cost	Manufacture	Adaptive	Compatible	Utility	Total
Adaptive Foot	1	2	1	1	2	1	8
Rounded Foot	2	2	3	2	1	2	12
Ankle Joint	3	2	2	3	3	3	16

Table 5.1: Foot Design Matrix

As visible in the table the team decided to go with an ankle joint design. The team slightly modified it to fit the system best. The foot was 3D printed out of Thermoplastic Polyolefin (TPO) and attached by a custom machined part. The limit switch was placed between the TPO and the machined part. TPO was selected as the material as it is elastic yet durable. More variation of each joint can be seen in the appendix.

5.4.2 Leg Design

The leg was also redesigned to be slimmer and stronger and most importantly reduce slack from the sprocket gear train of the prior leg. Since the series elastic actuation was found to introduce so much slack it was entirely removed. The motors were rearranged to directly drive each joint. This would require an entirely new leg to be built or drilling different mounting holes onto the current lower leg. The team opted to make a new leg to allow for further improvements and the ability to add a new foot design to the robot. The SEA hardware was

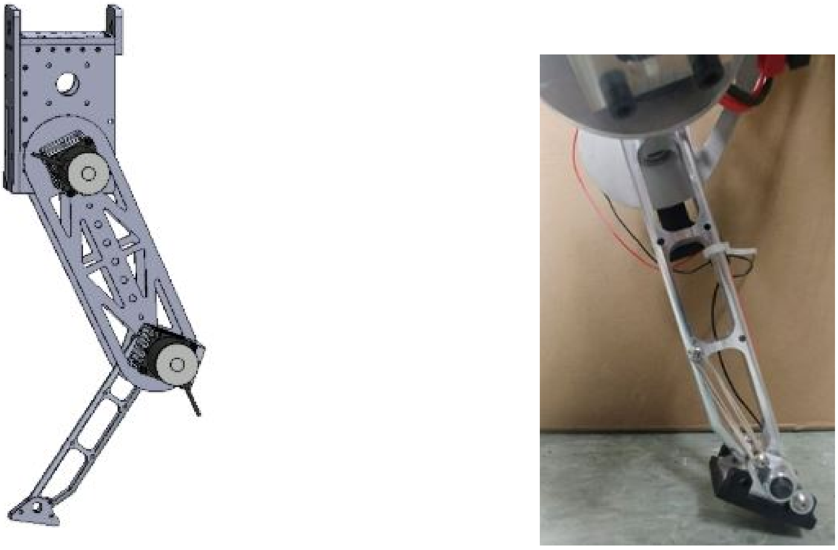

(a) Foot Redesign CAD (b) Redesigned foot on Robot

Figure 5.14: Foot Redesign

also removed due to electronics and hardware restrictions. The pots chosen for the quadruped did not have enough accuracy to properly incorporate the SEA system. The setup from the last MQP would also need different springs for the compliance as the deflection from external torques were not high enough to be measured. Without the SEA the bottom part of the leg was made much thinner and designed to allow for a spring loaded ankle joint. The new bottom halves of the legs are approximately 30% of the weight of the previous bottom halves. The primary purpose of the redesign of the bottom half of the legs was just to accommodate the newly designed feet. However, the new bottom link is substantially lighter than the previous version. The top half of the legs could also be designed and machined in a similar fashion, but this was deemed unnecessary for the current project. The main advantage for redesigning and making new top halves to the legs would be cutting weight. The bottom half of the legs were entirely re-machined out of aluminum. The re-designed lags can be seen in Figure 5.14. The parts were designed in SolidWorks before they were cut and a stress analysis was done to ensure that it could support the robot. The results of this analysis is shown in Figure 5.16. The analysis shows that when torque is applied more of the force will be applied to the sides of the piece towards the top of the part. While the points where the axles make contact the piece take a lower amount out load, this helps minimize the risk of stripping. It showed that the piece was strong enough throughout the design to support the robot and it's application as a joint.

Figure 5.15: Redesigned Legs

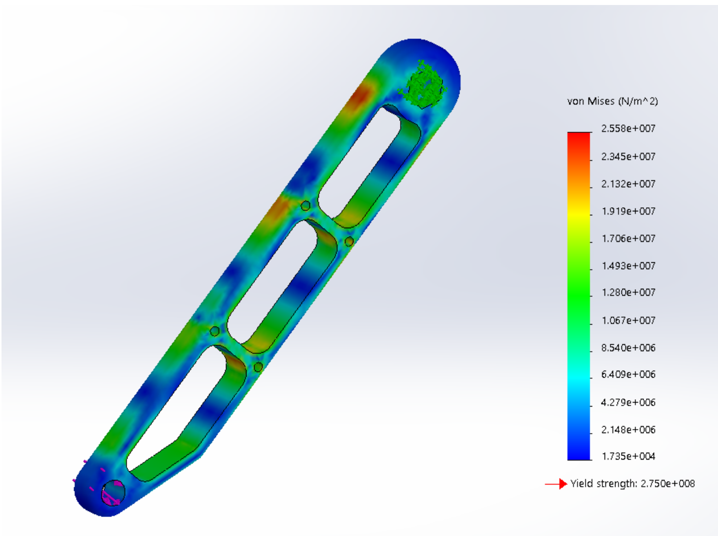
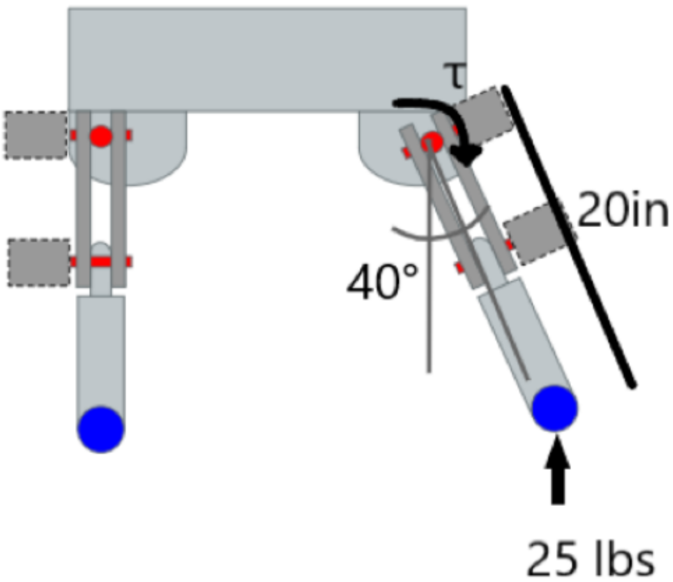


Figure 5.16: Leg Finite Element Analysis (FEA)

5.4.3 3rd Degree of Freedom

A third degree of freedom that moved the legs perpendicular to their current plane was implemented for two reasons. The first was to allow for a turn gait to be developed which would require the third DoF. The second leading reason is that the third DoF allows for improved crawl and walk gaits by allowing robot to create a wider stance which improves the resultant support polygon. All four legs now include this third DoF.



Perpendicular distance from force:

$$sin(40°) \cdot 20in = 12.86in$$

Torque calculation from distance:

$$25lbs \cdot 12.86in = 321.4\ in \cdot lbs$$

Figure 5.17: Torque Calculations

To implement the third DoF, the team needed to spec and buy new motors and gearboxes. Under normal operation, the team determined the third DoF would never need to exceed 40 degrees out for fully extended legs and half the robot's weight, which is approximately 25 lbs. The free-body diagram and equations used can be seen in Figure 5.17. The torque required for this situation was calculated. The torque calculated was 321 in-lb. To always remain above half stall torque, the team began looking for motors with at least 800 in-lb stall torque. Speed of the motor became the next consideration. Based off of the experience of using the already existing two joints, the team wanted the joint to be able to move 120 degrees in half a second. That corresponds to 40 rpm. A BaneBots motor and 444:1 gearbox were chosen for their low price and resultant specs being 1940 stall in-lbs and 43 max rpm. However with max load the RPM is 34. While this is below our desired RPM the team decided to still go with these specification as it provided sufficient torque with only a small sacrifice in speed.

Mechanical changes had to be made to implement the third degree of freedom. The leg which was initially fixed at the chassis at the shoulder needed a free rotating joint. This convention for labeling joints and their axes is used to generate the inverse kinematics equations. Figure 5.18 below shows how the team placed all the necessary components. Different angles of this install can be seen in the appendix. The Spark controllers were installed close to the motors for wire management and the potentiometer was mounted on the outside of the chassis for easy access in case it needed repair or replacing. Figure 5.19 also shows the CAD of this installation so the attachment of the motor to the leg is visible.

With the introduction of the 3rd degree of a new analytical solution for inverse kinematics must be derived. The new base frame for an individual leg was also moved to the newly implemented joint. The base frames z-axis is not in the direction of rotation to maintain the same orientation of the x-axis facing towards

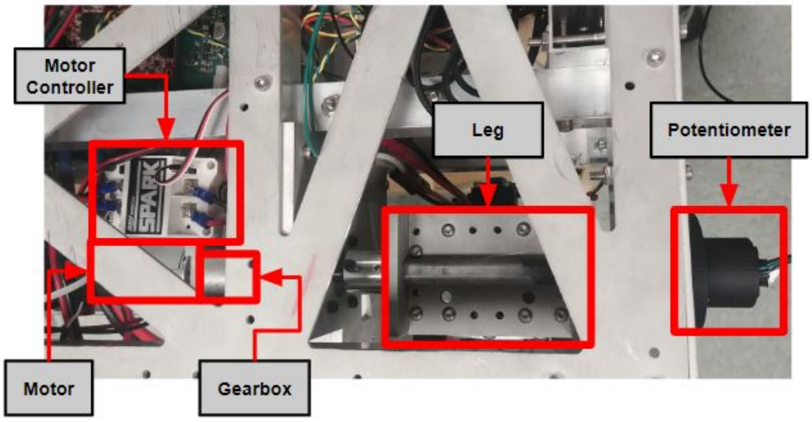


Figure 5.18: 3DoF Components Installed

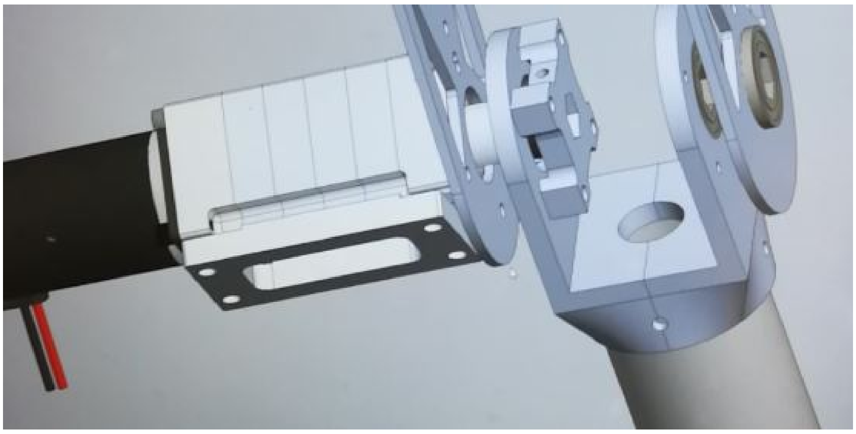


Figure 5.19: 3DoF CAD

the front of the robot. The new kinematic chain and frame assignments can be seen in Figure 5.20. Each degree of freedom and its rotation is labeled following Denavit-Hartenberg (DH) convention. The DH convention is a way of labeling axes in a standard manor to ease the generating of kinematics equations.

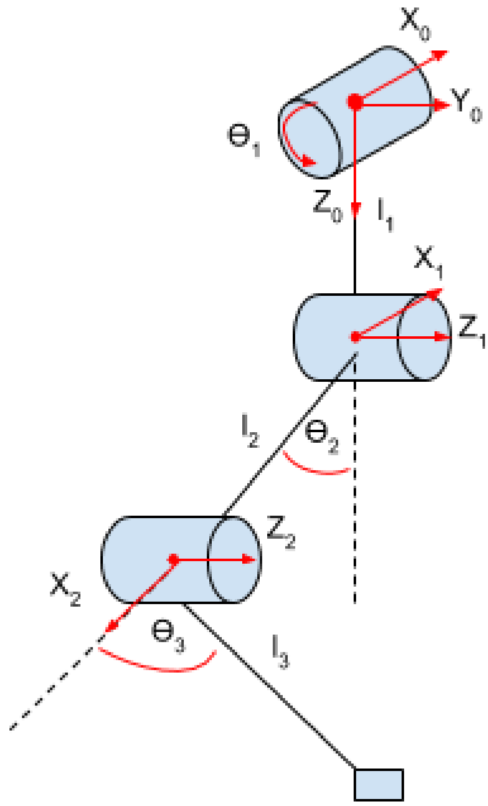


Figure 5.20: Kinematic Chain of Single Leg

$$H = sqrt(y^2 + z^2) - l_1 \tag{5.3}$$

$$\theta_1 = atan2(x, z) \tag{5.4}$$

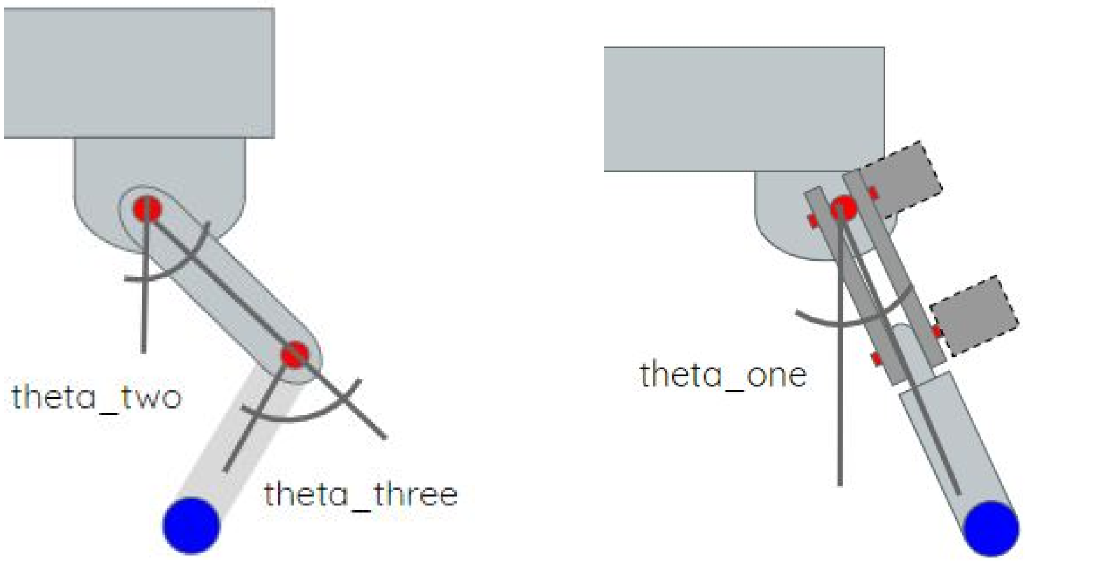
$$\theta_3 = acos(\frac{x^2 + H^2 - l_2^2 - l_3^2}{2 * l_2 * l_3}) \tag{5.5}$$

$$\theta_2 = atan2(x, H) \pm atan2(l_2 + l_3 * cos(\theta_3), l_3 * sin(\theta_3)) \tag{5.6}$$

A standard approach for solving the inverse kinematics for the typical kinematic chain was utilized and the equations can be seen in equations 5.3 to 5.6. θ_1 is first calculated from the arctangent of the desired y and z value. The value H corresponds to the new height the last two DoF's must travel to reach the setpoint. θ_3 is calculated from the law of cosines of the triangle. Then θ_2 is calculated based on the result of θ_3.

During testing of the walking gait a decision was made to have the front legs go the opposite direction from the back legs. This helps to maintain a more centered center of gravity with less variance in the center of gravity. The inverse kinematics remain mostly the same. θ_3 is multiplied by -1 for the front legs. and θ_2 uses the negative sign for $\pm$.

The location of all three joints on the leg is shown in Figure 5.21. Theta one is the new shoulder degree of freedom and two and three are the original one.



(a) Leg Joint Angles (b) Front View Leg Joint Angle

Figure 5.21: Joint Angles

5.5 Unanticipated Issues

Most engineering projects encounter unexpected situations and have to make decisions quickly that will move the project forward. This is especially common when the basis of the project was another development project that was not fully tested. One of the first issues the team encountered was the communication between the MicroZed and the Teensys. As mentioned, having real time communication was vital so the team had to spend time changing the method of communication, which was not initially anticipated. The team also found that the slack in each joints caused major problems and that the SEA was responsible for a lot of it. The team had originally planned on using the SEA but given the state of the system the team made the hard decision to remove the SEA and make each joint direct driven. This was a time consuming decision that replaced a previously anticipated component of the project, however the team felt this was necessary to achieve the larger project goal. The previous MQP had also only installed 180 degree potentiometers. This was an issue as the team wanted longer walking strides and unless the potentiometers were perfectly mounted they often hit their limits and broke. So the team decide to make time in the schedule to replace each potentiometer with a much more durable 280 degree pot. The team also installed a 3D printed mechanical stop so that if a joint over extends itself it will not immediately break the potentiometer. One of the last major problems the team had was configuring the eproms. The previous team made each Teensy have an individual ID so they needed entirely separate code despite doing essentially the same thing. This also meant that if a Teensy was reset the ID could potentially not match what was expected and the robot would simply not run. Since there was no documentation of this it took the team a long time to figure out what was causing these recurring issues. The team decided to re-configure the Teensy ID's so only one file needed to be uploaded to each and would automatically match it's ID. The team was able to effectively tackle each of these issues during the course of the project without sacrificing the projects main goal.

6 Results

As stated, the goal of the project was to prove the potential use of the quadrupedal robotics platform as a tool for future projects within WPI's Robotics Engineering program. The team demonstrates this by implementing stable and intelligent motion gaits. Through physical tests, the team also made modifications to improve the entire system as well. The results of this project are outlined in this section.

6.1 Mechanical Analysis

Throughout the course of this project the team made many mechanical modification. Most changes were unplanned and the result of unanticipated issues. Modifying and upgrading some of the structural components, such as replacing 3D parts with machined parts, made the overall chassis and leg more rigid. This made programming and tuning the gaits much easier. There were still many mechanical variables that made the gates unstable.

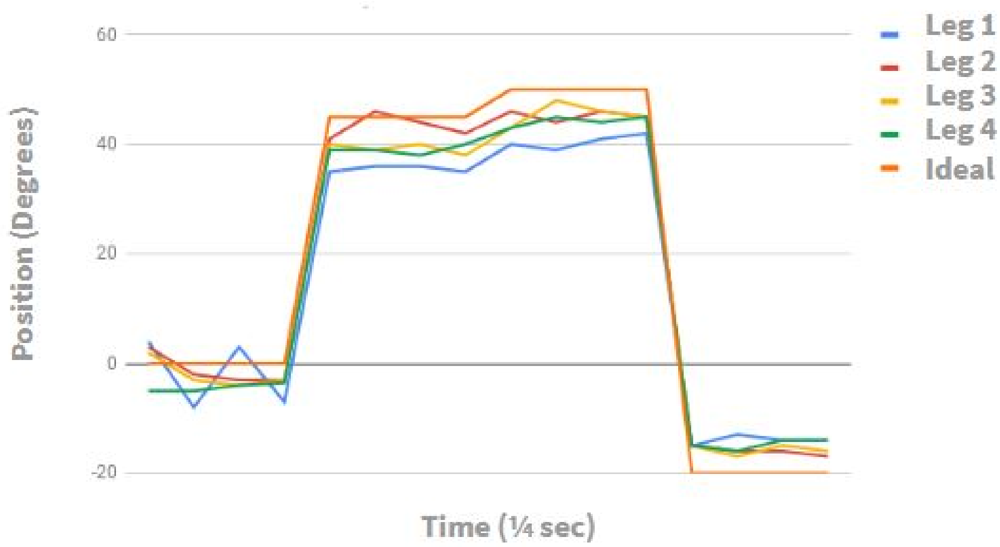
6.1.1 Leg Design

Slack

The amount of slack caused by the Series Elastic Actuation created a lot of issues. Removing the SEA improved the system's accuracy and stability. The slack per joint improved from roughly thirty degrees to about fifteen degrees. Figure 6.1 displays two graphs showing the accuracy of the top and bottom joints after the SEA was removed for all four legs. It is important to note that this was done in the air with no additional load on the joints. The code that was run included PID, which took input from the potentiometers mounted directly on each leg.

As visible from the two graphs neither joint is 100% precise. The bottom joints are significantly more accurate on average than the top joints. The team believes that this is because the top joint carries twice the weight the bottom joint carries and experiences more torque, making it harder to reach its position. The team accounted for this by having separate PID values for the top and bottom joints. Initially the bottom joint would be about twenty degrees off and the top joint was about thirty degrees off at any given time. Removing slack lowered the error to about five degrees for the bottom joint and ten for the top. This left over slack was caused by the four stage VEX Versa planetary gearboxes. These gearbox created a backlash of three to five degrees per joint. This rotational tolerance was doubled through the hex bores made for the axles as they did not perfectly fit.

(a) Slack in Bottom Joints



(b) Slack in Top Joints

Figure 6.1: Slack After Redesign

Weight and Adaptability

After removing the series elastic actuation in the legs the team re-designed the feet so that they could be better suited for motion. These two changes required the bottom half of the leg, to be redesigned in order to mount the motor directly on the joint it actuation's. The new redesign also had to ensure that the foot could be easily attached by an ankle joint. This process reduced the weight by a pound and a half per leg. In the process of replacing parts of the leg the team also found pieces of the chassis that were not vital to the stability or structural integrity of the quadruped. These pieces were removed to allow future projects more space and weight to add sensors or other components. This increases the platform's adaptability to future projects. The foot design implemented is also much better suited for motion as it makes more contact with the ground at the various phases of the crawl and walk gait.

6.2 Torque Sensing

Removing the SEA also removed the leg's capability of torque control. While the team thought removing it was necessary for stability the team wanted to find a way to replace the torque sensing capabilities. One method of accomplishing this is through current sensing. If the motor draws more current to stay in position it is an indicator that it is under a larger load. The team tested this by inserting a current sensor into the system and sent that output to the MicroZed. However the current sensors used required five volts of power, and the Teensy's can only output 3.3. In order to give full power the team would need a voltage stepper. As a result the readings were very noisy and its neutral reading was 510. This limits the range. When applying force to the foot only the bottom joint shows a change in torque. This is expected based off the legs orientation. Theoretically the team can get by with just one sensor per leg but when the bottom leg is almost parallel to the ground we would need the top joint torque as well. The team decided to continue with this as there was not enough budget to buy eight current sensors and voltage steppers in order to make this method reliable.

6.3 Motion Gaits

The team successfully implemented all three motion gaits. They are stable, however, they are not precise and over time they start to slip. This is true for each gait. The successes and issues for each are discussed bellow.

6.3.1 Crawl Gait

The crawl gait was the first motion implemented in the robot. The goal of this was not speed but stability and to prove that stable, intelligent motion was possible with the system. The crawl gait successfully showed this and helped establish the expectations for the rest of the project. While it is still not perfectly stable, the team identified the issues causing this and fixed what could be done given the time and money restrictions. The fastest stable gait the robot can achieve is about twenty seconds per full gait. A full gate is defined from the start of the state machine until the end, meaning that every leg has moved once. For the crawl gait this moves the robot about ten inches forward making the speed about 150 ft per hour. This motion was implemented before the third degree of freedom, so it only utilizes two joints per leg. Despite having limited motion the team was able to keep the center of gravity within the area of stability throughout the motion.

The team found that much of the unsteadiness was caused by the slack in joints. As mentioned the team addressed this issue and reduced slack, increasing the stability. However, there was still enough slack to cause oscillations at times in the crawl gait. It causes error to build up over time and after about five full crawl gaits some of legs start to slip or drag. For now, the team has addressed this issue by including pauses between each full gait to allow the robot to readjust if necessary, this is a non-ideal solution that was only implemented because of time restrictions. Throughout the motion, the weight on the leg varies a lot making tuning the PID controller difficult. The team implemented feed forward to help with the changes in force on the joints but there is still room for improvement. The team also found that the initial stance for the robot intended by the previous team was not ideal. The stance was changed so the knees face opposite directions, this helps distribute the weight of the legs, better centering the center of gravity. It also helped the robot avoid toggle points in the joints that caused an excess of force on the motors. These toggle points were identified to create predictable unsteadiness due to the backlash in the gearboxes. The new stance also allowed the robot to make larger steps. It was one of the simple design changes that the team made that made a big difference. The two stances can be seen in Figures 6.2 and 6.3.

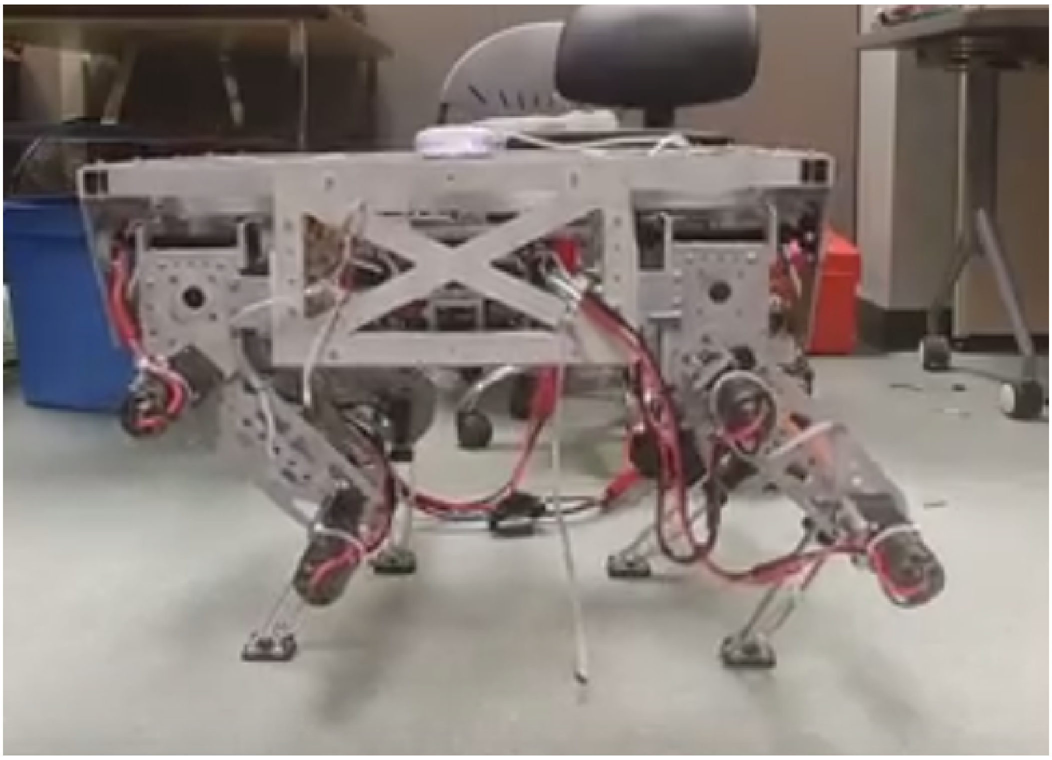


Figure 6.2: Quadruped Old Stance

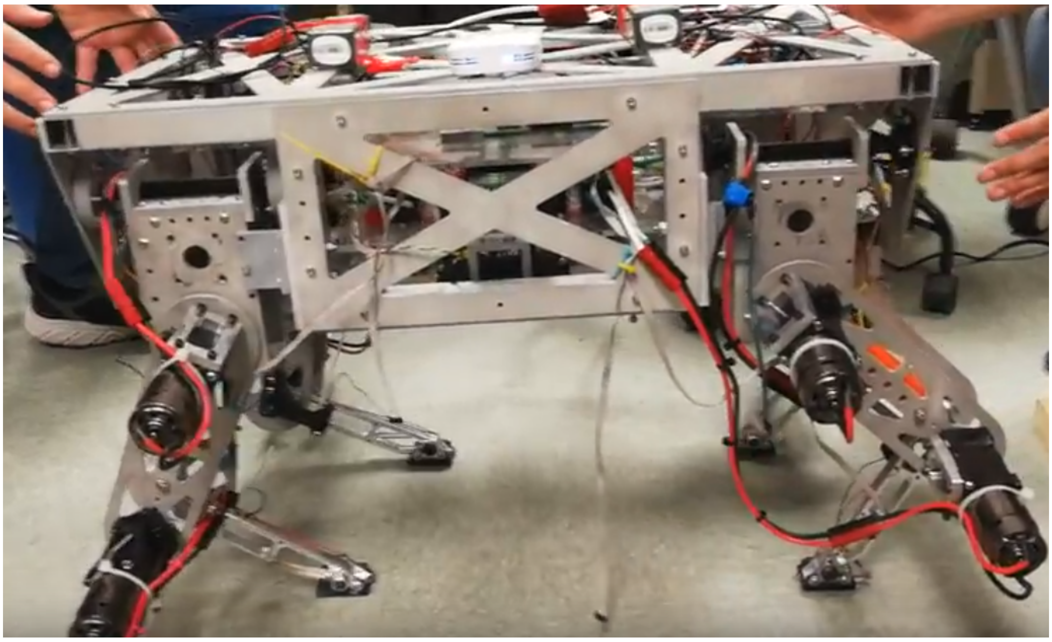


Figure 6.3: Quadruped New Stance

6.3.2 Walk Gait

The walk gait was the second motion gait implemented. The goal of this gait was to challenge the stability of the robot from the crawl gait and to increase the speed. Since this gait lifts two legs at a time the gait needs dynamic stability. However, since the robot was moving faster, it removed some of the inaccuracies from the crawl gait. The robot moves two legs at a time, so the entire gait consists of two main gait motions. This gait was tested by running the walk gait around across the robotics lab space in 85 Prescott. However, some of the issues found in the crawl gait were amplified in the walking gait. Since the motions were faster there was less time for the motor controllers to account for the slack, so the feet often dragged because of the slack dragging it down. While each step moved a smaller distance than each step of the crawl gait, it moved faster and thus covered more distance over time. Using the walking gait, the robot can move about six inches per second, 255 feet per hour.

6.3.3 Turn Gait

The turning gait was the last thing the team implemented and had the least amount of time to test and tune. Because of this the turning gait was the least stable gait but was still implemented enough to shown potential for stable and intelligent turning. Much like the crawl gait, the turn gait lifts one leg at a time making it statically stable. However, when the robot rotates its chassis oscillations occur making it unstable. The implementation of this gait was also not part of the project plan outlined at the beginning of the project. As a result, the design of the foot did not account for a potential third degree of freedom and the angles the foot may make contact with the floor.When the foot reaches out away from the robot it makes very little contact with the ground making it very unstable. This limits the degrees it can turn at a time. Since this design was a big issue for the turning gait the team added a slight curve in an attempt to allow the foot to make contact are the various angles of the turning gait. The team did this by adding a 3D printed fifteen degree curve to the bottom of the foot. The curve added is shown in Figure 6.4. While this helps the robot turn slightly

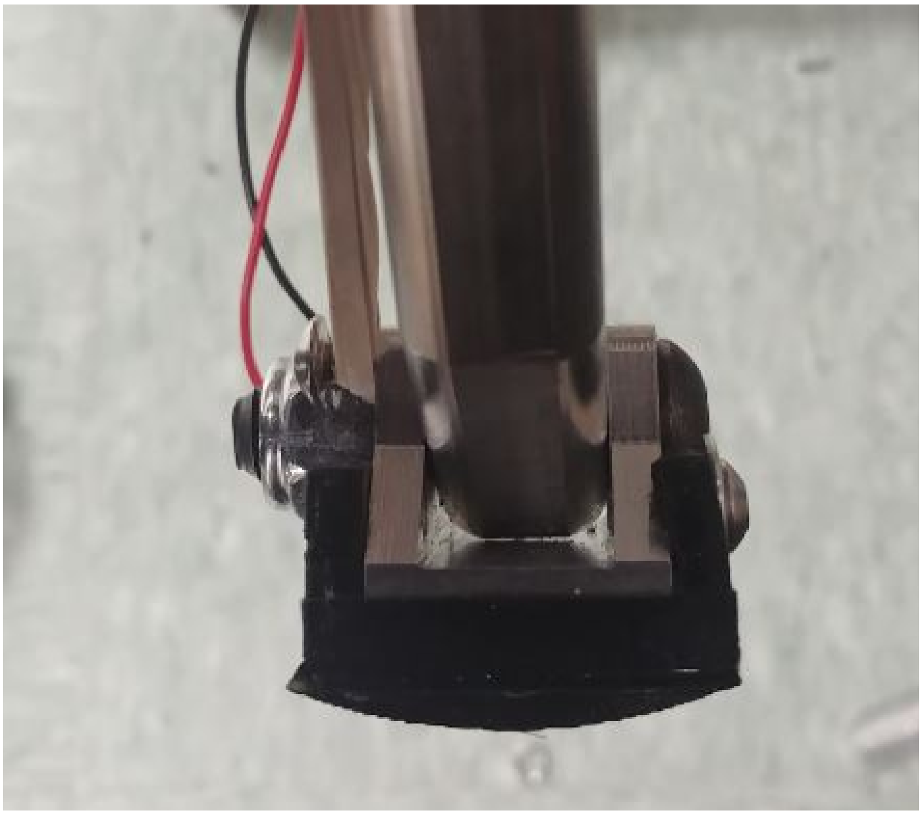


Figure 6.4: Temporary Foot Fix

more the turn is also restricted by the max angle of the foot that still activates the limit switch. In theory, the quadruped can turn up to forty-five degrees at a time stably if these issues are resolved. However, the robot is currently limited to about twenty degrees of stable turning. The limit switch is not always activated beyond this angle. Adding a third degree of freedom also introduced different angles of force on the legs and joints. Certain mechanical systems encountered stress that they were not designed for, specifically, some of the 3D printed parts that hold the legs and its components in place started to splinter and break. The team replaced these but did not have enough time to fully develop a solution.

6.4 Electrical Analysis

Since many changes were made to the robot that were not accounted for in the design a lot of the electrical changes were not neatly organized. Many of the parts to hold the sensors were 3D printed and wires were soldered into the Teensy, this is messier than the original project intended as the previous team designed a custom shield to organize the all the Teensy's inputs and outputs

6.5 Communication Analysis

The majority of the communication between all embedded systems successfully functions through CAN lines. CAN has proven to be robust and without causing an error in the quadruped. For the implementation of the third DoF, the motor controllers utilize PWM. If we had the choice to continue to use CAN we would have, but the Spark motor controllers were chosen primarily for their low price and do not have CAN capability. Still, PWM has been a simple solution for the current implementation of voltage control of the top joint. All communication is completed in different loop cycles on both the main controller and the leg controllers. Joint PID control communication occurs in five millisecond loops. The central controller can send all four legs their joint positions at the same time in real time. Similarly, if the central controller requests data back from a leg controller the response is also in real time. When the leg controller receives a message from the central controller it temporarily interrupts the main PID loops. However, the handling of a message from the central controller is handled quickly enough to never affect the real time control of the joint positions.

6.6 System Analysis

The system as a whole functions well enough to accomplish stable gaits, however, the combining imperfections of the system as a whole could prevent near perfect gaits in the future. The system is completely unaware of the slack in its joints and does nothing to account for it. Presently this is not a large issue, because the PID control eventually makes up for the slack. However, it is apparent in the walking gait that the feet do not get much lift off of the ground. The walk gait takes such quick steps that the PID can not cover for the slack completely before the end of the step. The combination of imperfect PID gains, and slack when lifting legs cause slightly wrong placement of the legs when placing them. This misplacement can lead to future instability as the foot may slide to re-correct with the kinematically correct position. With the current state of the robot, no stability correction is implemented so instability from wrong foot placement can lead to future instability or failure.

6.7 Budget

As frequently mentioned in the paper budget was a limiting factor. The team utilized all the money provided by the robotics engineering program for the MQP. Most of the funds were spent on repairs and on the installation of the third degree of freedom. Below is the team's final bill of materials. Every purchase was analyzed by the team; the basic requirements were weighed against cost. The team often had discussions regarding the project's priorities to decided where it was worth spending money. A finalized list of the team's purchases is shown in Table 6.1. Improving individual small parts of the system will could lead to great improvements to the consistency of the system. What is not included in the table is the cost of custom made materials; since the team acquired materials and made them in-house gauging the exact cost is difficult. The custom materials include the machine cut legs, and the 3D printed feet.

Item	Purpose	Quantity	Cost ($)
Potentiometers	Position Sensing	12	30
Lipo Batteries	Power	2	110
Limit Switches	Contact Sensor	4	5
Spark Motor Controller	Should Joint Control	4	160
Gearbox	Gear shoulder for Torque	4	340
		Total	$ 645

Table 6.1: Project Costs

7 Recommendations Moving Forward

The purpose of this project was to ensure that this quadrupedal robotic platform has the potential to serve as a useful tool for the WPI Robotics Engineering department. With the goals of this project accomplished the team can confidently recommend to continue work on this project and has identified several ways to move forward in development. Given more time and funding the team is confident that the robot can be used for the development and testing of other projects such as navigation and path planning of a quadruped. There were also issues that the team encountered that need improvements. This section should be referenced by any future team who would like to continue to build upon the quadrupedal platform.

7.1 Recommended Improvements

Through vigorous testing, multiple opportunities for improvements were found. The team addressed some of these, but because of restrictions in time and funding, they could not all be resolved. The team recommends that future projects address these issues. The issues identified were identified to have a large effect on the robot's stability, and control.

7.1.1 Mechanical Redesign

The first area of improvement is the physical robot. The robot originally weighed about 40 pounds; the team was able to lower that to about 35 pounds. However, there is still room to lower this weight. Making a lighter weight robot would put less stress on the motors. Future teams should also make additional room for additional components that may be added for other projects. Another issue with the mechanical chassis was that it was extremely difficult and time consuming to take apart. Replacing the potentiometers on the top joints required taking apart the entire chassis and pulling the leg out. This made any kind of modification or repair extremely time consuming. So a future project could partial redesign the chassis to make repairs or adjustments easier.

7.1.2 Leg Redesign

One of the most significant issues the team had was the amount of slack in the system. While removing the series elastic actuation reduced slack in each joint by about 30% there was still about 15 degrees left. This causes instability in the leg as it can move when it's not supposed to. The team analyzed the sources of slack and found the main issue was with the gearbox. Replacing these would be simple but costly. A future team could also work on the foot design. Since the team originally designed the feet with only two degrees of freedom in mind improvements could be made so that it adapts to impact while turning as well. A team could also continue development and testing on the custom foot sensors. They lack adequate testing or any correlation between readings and usable data. More information on these sensors can be found in the previous teams final report. (Armsby, et al.)

7.1.3 Sensors and Controls

While the sensors the team installed were sufficient for our goals, there is a lot of room for improvement. Installing an IMU has a lot of potential to increase stability. Including the chassis position throughout the walking gate in a feedback loop would allow the robot to recover when it starts slipping much more reliably. The difference in stability would be very noticeable in the walk gate to help dynamically balance the quadruped.

7.2 Compatible Future Projects

As mentioned, the goal of this quadrupedal robot is for use in for projects. With the improvements and added capabilities there are a lot of areas such a platform could be of use.

7.2.1 Path Finding

Path Finding and navigation capabilities could be run on the quadruped. Such a project would require the installation of sensors to help determine the robot's position. Adding such sensors is possible since the team trimmed down the weight of the robots. This would work especially well since it allows physical tests and the main code can be run and modified wirelessly.

7.2.2 User Interface

While this platform is designed to be used for development, it can also be made more user-friendly. Once the quadruped's motions are sufficiently stable and reliable, it will be used for higher-level use. So having a user interface to do this would make the process much easier. This interface could either be a comprehensive graphical interface or clear and organized command line interface. The development of such an interface may require some restructuring to make it useful.

8 Conclusion

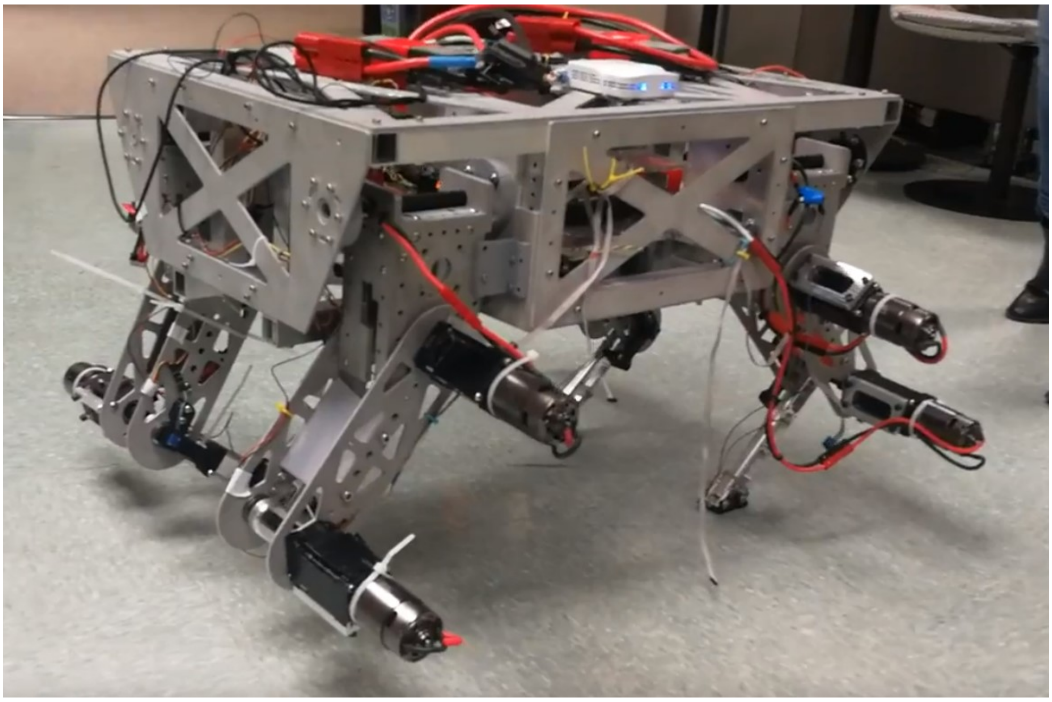


Figure 8.1: Final Robot

The main goal of this project was to ensure the quadrupedal robotic platform's potential as a useful tool in the development of future project in the WPI Robotics Engineering program. This goal was successfully met through the implementation of three motion gaits. The robot is able to crawl, walk, and turn stably and intelligently. The final state of the robot can be seen in Figure 8.1. This project covered a broad range of robotics disciplines as each member had to work in mechanical design, electrical design, and code design. Each of these three disciplines served a vital role in the completion of the project.

As this project serves as a capstone for the team's undergraduate robotics engineering experience, it incorporated and built off many of the skills taught in the WPI robotics course sequence. The use of PID and basic feedback systems were taught throughout the sequence and the team took that information and built upon it to create a feedback system that integrated PID to intelligently walk and balance. The team also had to implement both forward and inverse kinematics which was first taught early in the robotics sequence.

From the start of the project, the team understood the challenges that come with working with an untested freshly developed system. The team understood that issues would arise from testing that would require modification, but could not predict ahead of time which parts of the system would need modification. The team prepared for a constantly changing timeline. Because of this the team was still able to finish the original goals set out. When the team saw that we finished parts sooner than expected, we quickly added the third degree of freedom to the schedule.

This project successfully tested and proved methods of creating stable motion gaits. A lot of potential has been shown and the team strongly encourages future teams to continue and build upon it to make it valuable tool for future WPI Robotics projects.

The teams finalized gaits can be viewed at the following link:

https://youtu.be/zxJvGyhcxtI

9 Appendix

The Appendix contains images and diagrams that are not necessary in the paper but may be useful or interesting to certain readers.

Figure 9.1 shows the design of the former teams leg design that includes SEA.

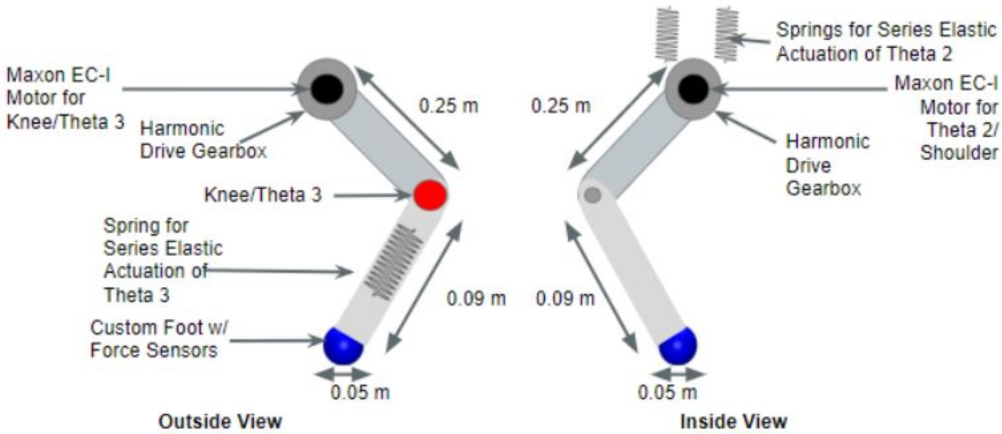


Figure 9.1: Detailed diagram of robots former SEA

Figures 9.2 to 9.4 include variations and designs considered for the robot's foot.

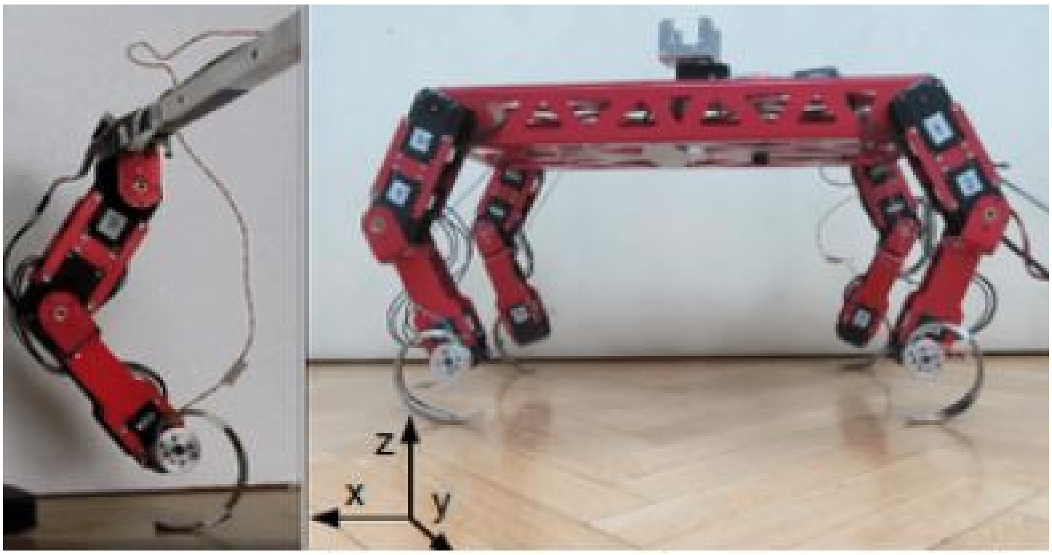


Figure 9.2: Rounded Foot Alternative) (Mutka, Alan, et al)

Figure 9.3: Different Angles of Adaptive Foot

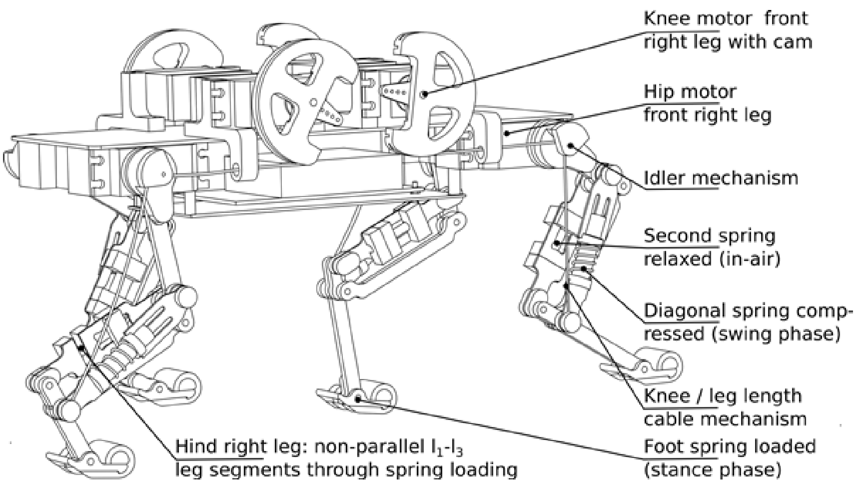


Figure 9.4: Elastic Angle Joint Cheetah Design (Cheetah-Cub)

The potentiometer mount in Figure 9.5 and 9.6 displays one of the mechanical changes made to the robot. These were 3D printed for every joint.

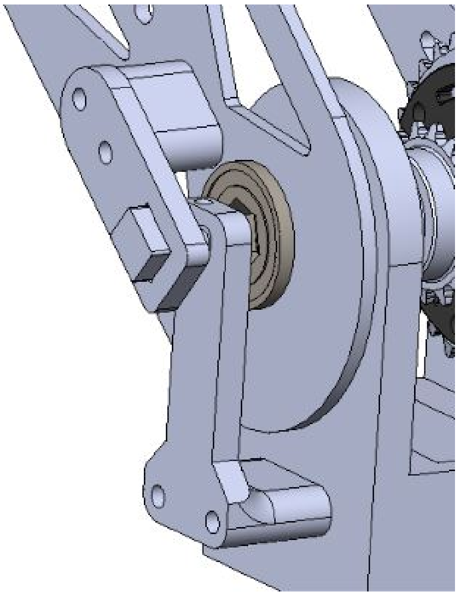


Figure 9.5: CAD of New Potentiometer Mount

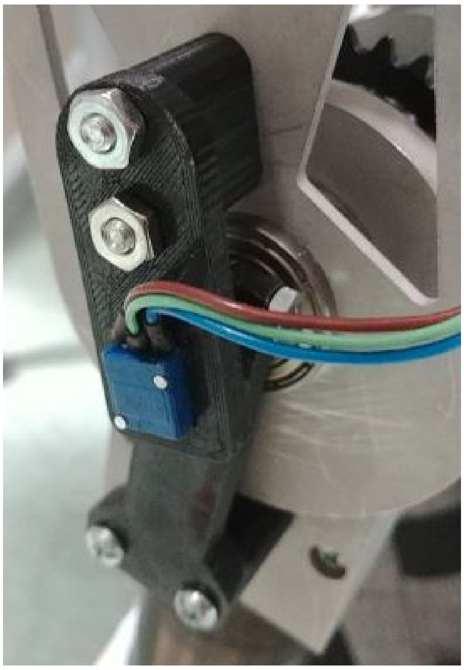
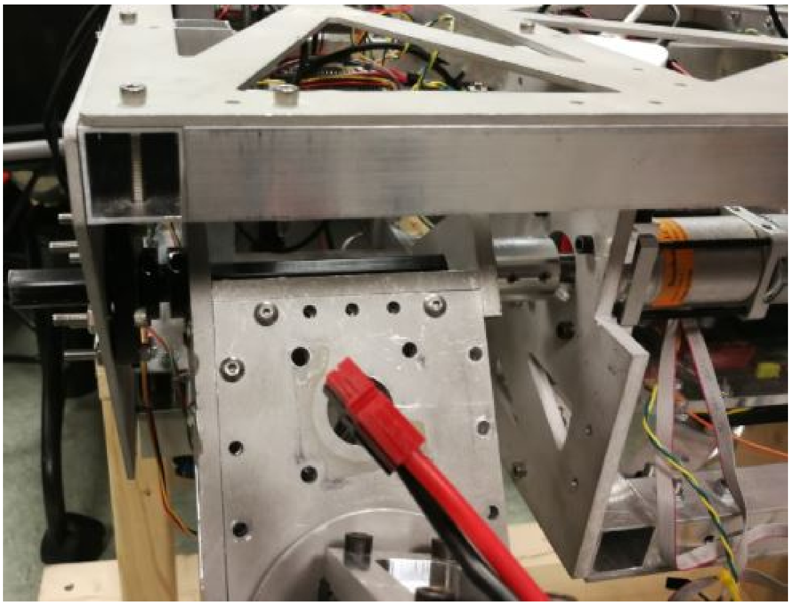
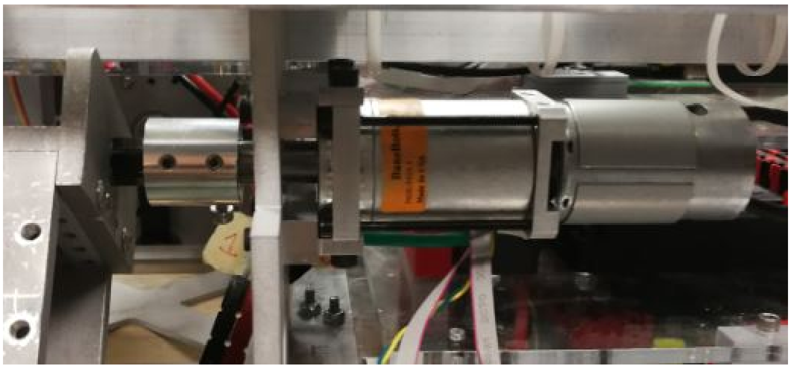


Figure 9.6: New Potentiometer Mounts

The images in Figure 9.7 show the motor installation for the third degree of freedom from various angles.



(a) New Shoulder Joint



(b) New Motor and Gearbox install

Figure 9.7: 3rd DoF Motor

Figure 9.8 has more specifications regarding the new batteries.

Figure 9.8: LiPo specs

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